Cluster of Excellence PRISMA+
Precision Physics, Fundamental Interactions and Structure of Matter

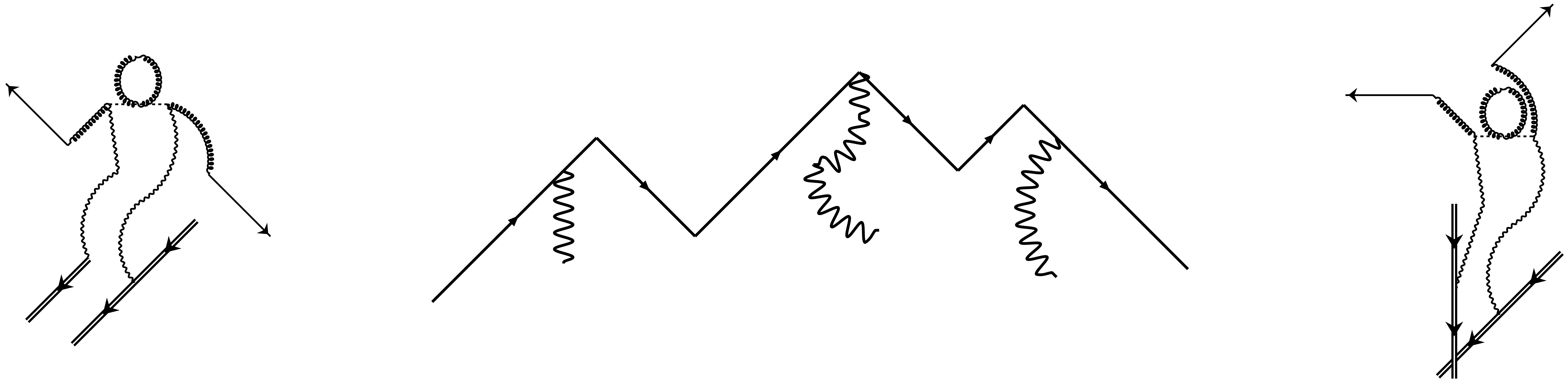
Mainz Institute for Theoretical Physics

Rencontres de Moriond since 1966

Global analysis of the *minimal* MFV SMEFT

Riccardo Bartocci, JGU Mainz

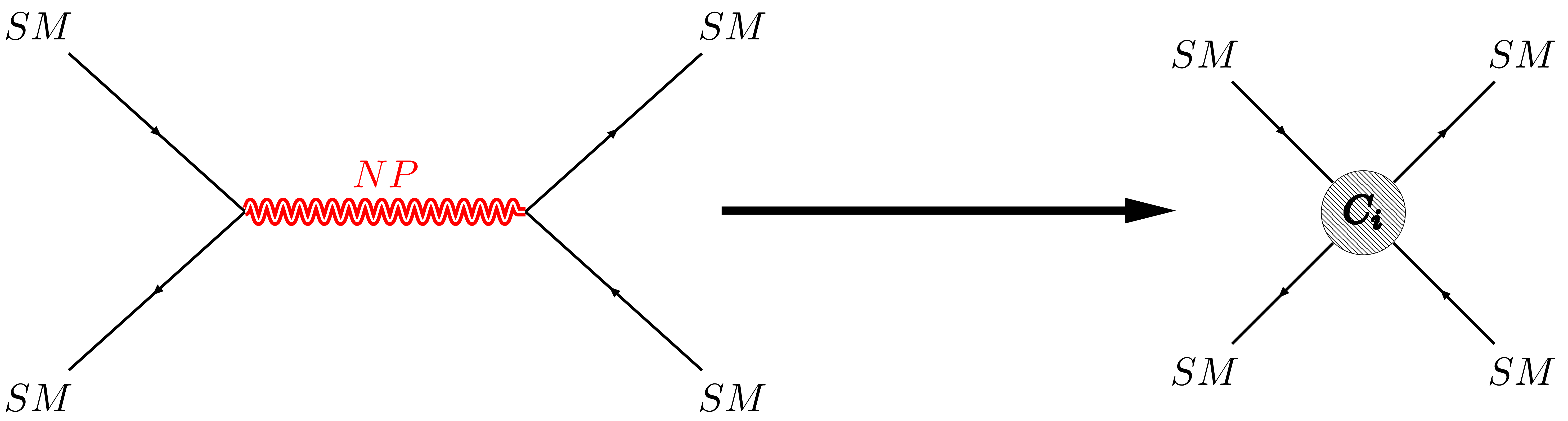
Based on work with A. Biekötter and T. Hurth (hep-ph: 2311.04963)



Rencontres de Moriond EW 2024, 26/03/2024

SMEFT and flavour symmetry

SMEFT is an EFT that allows us to study heavy NP in a model agnostic way:



$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2} Q_i$$

[arXiv:1008.4884: Grzadkowski, Iskrzynski, Misiak, Rosiek]

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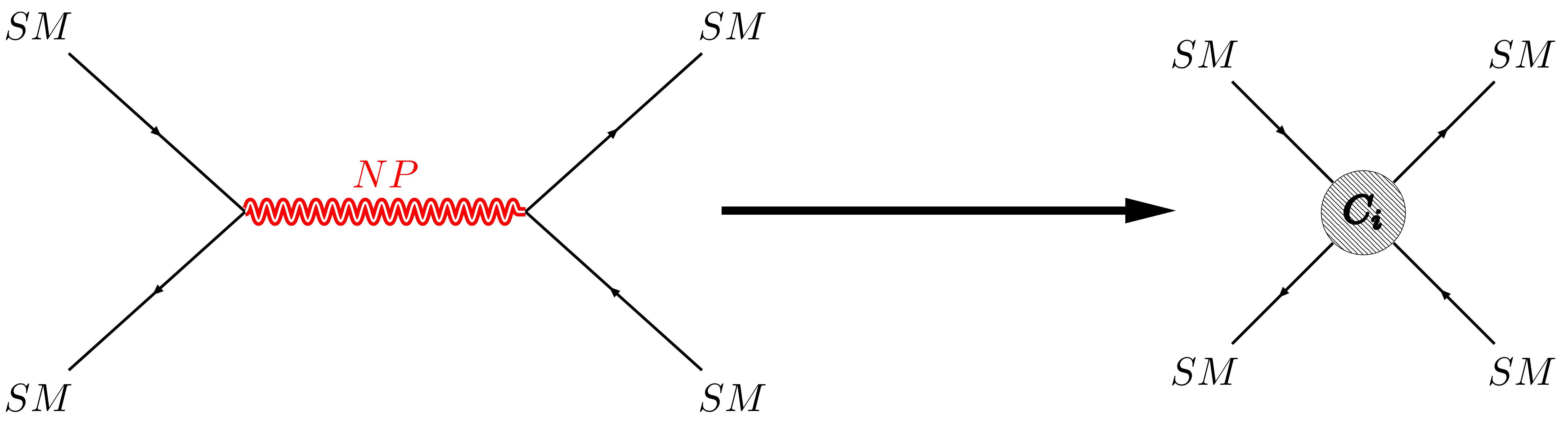

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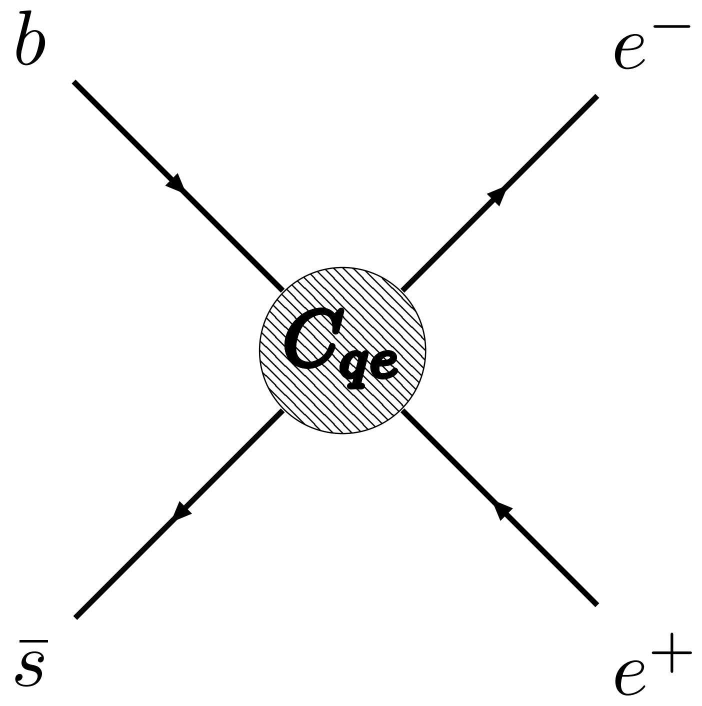
Symmetry assumption on NP:

$$U(3)^5 = U(3)_\ell \times U(3)_q \times U(3)_e \times U(3)_u \times U(3)_d$$



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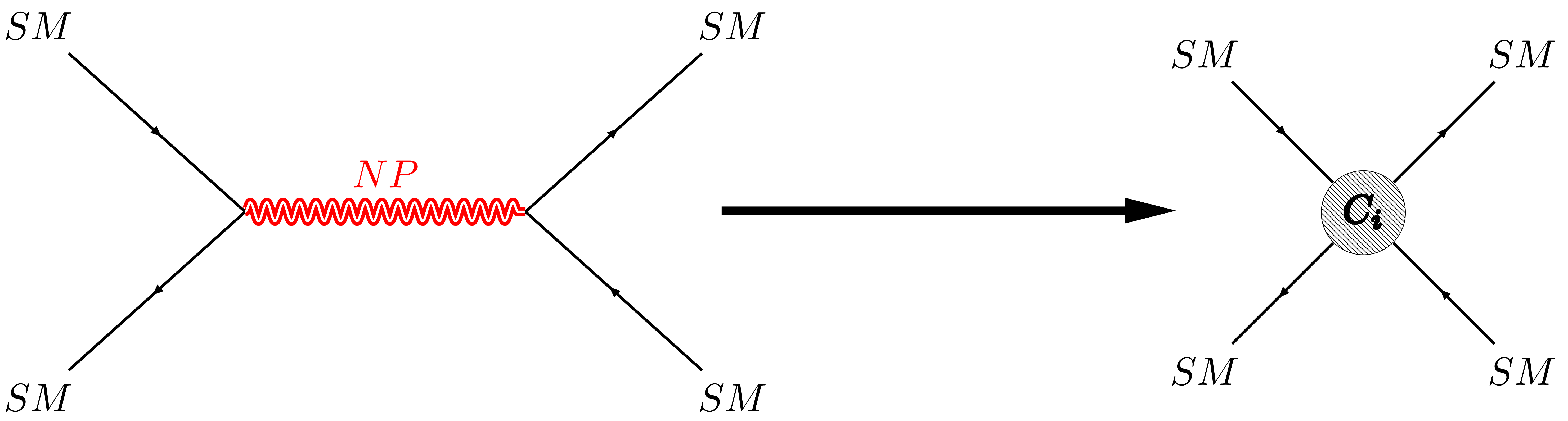

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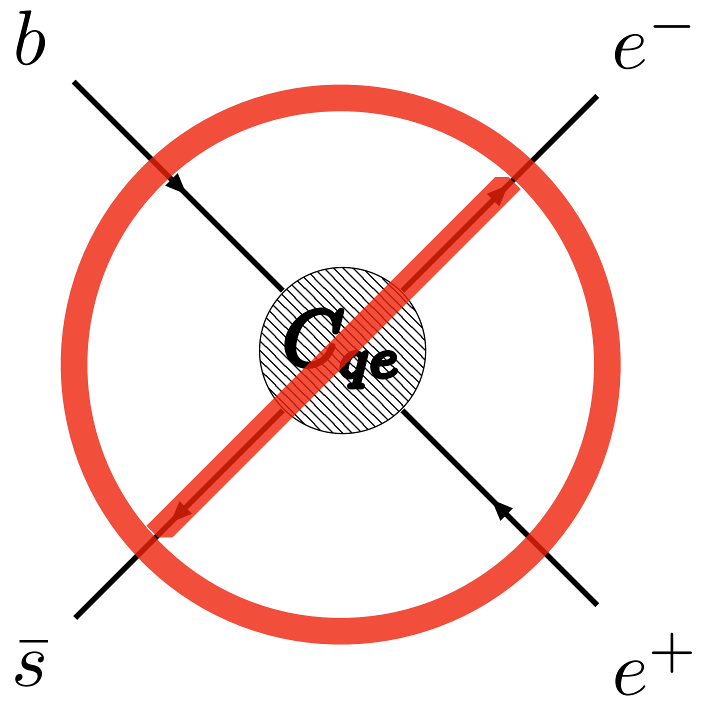
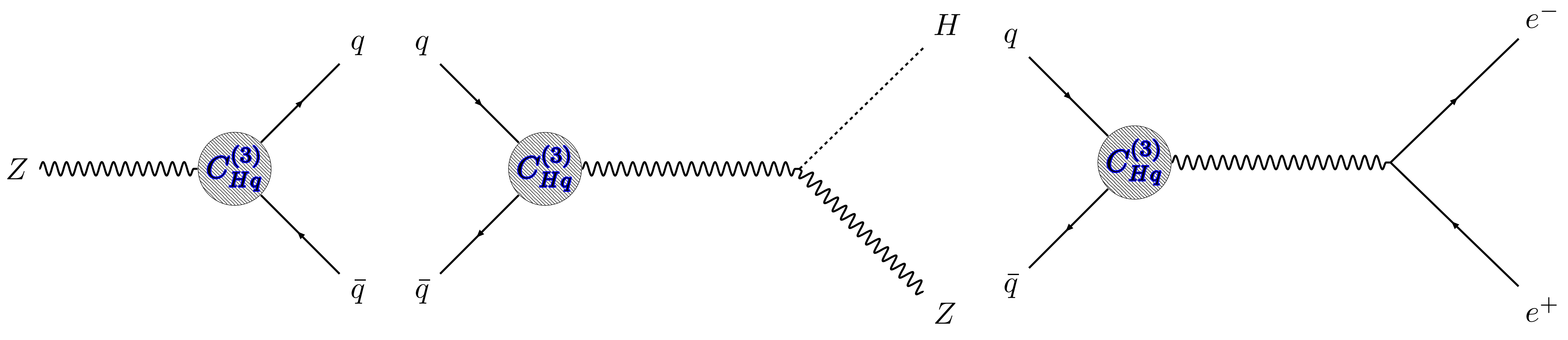


From 2499 dimension six operators to 41 (CP even)

[2005.05366: Faroughy, Isidori, Wilsch, Yamamoto]

Global analyses in the SMEFT

One operator influences different observables:



Z decay Higgs-Z production Drell-Yan process

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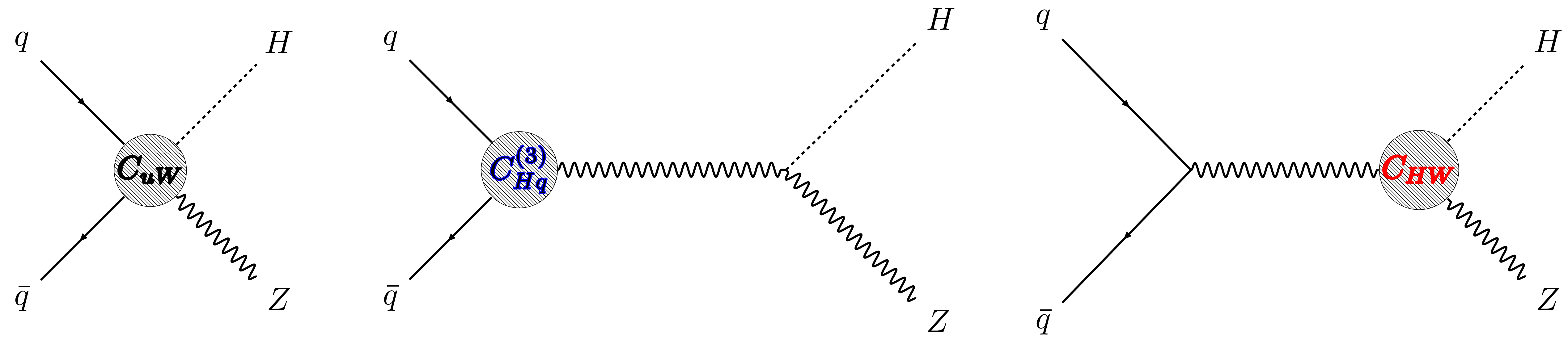

Higgs-Z production

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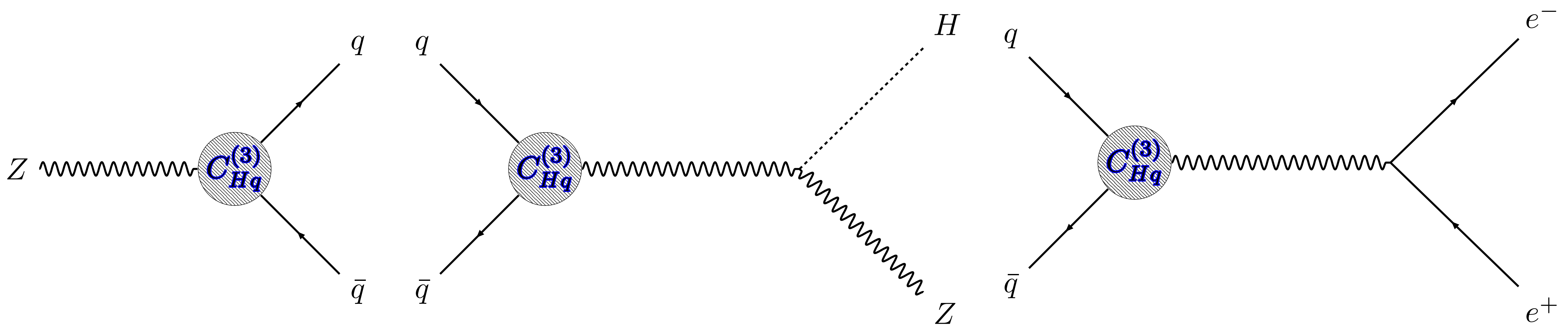

Z decay — Higgs-Z production — Drell-Yan process

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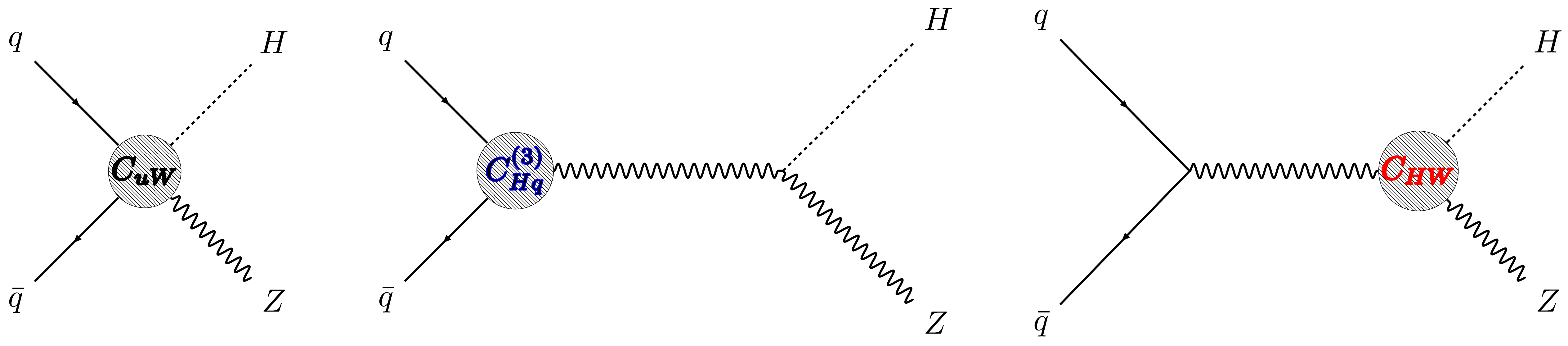


Higgs-Z production

Many different global analyses have been performed:

Combinations:
[arXiv:2304.12837: Grunwald, Hiller, Kröninger, Nollen]
[arXiv:1909.13632: Bißmann, Erdmann, Grunwald, Hiller, Kröninger]
[arXiv:2012.02779: Ellis, Madigan, Mimasu, Sanz, You]
[arXiv:2105.00006: Ethier et al.]

Low energy:
[1706.03783: Falkowski, González-Alonso, Mimouni]

Higgs-EW:
[1812.07587: Biekötter, Corbett, Plehn]
[1908.03952: Kraml, Quang Loc, Thi Nhung, Duc Ninh]
[2007.01296: Dawson, Homiller, D. Lane]
[2007.01296: Eduardo da Silva Almeida, et al.]

Top:
[arXiv:1512.03360: Andy Buckley, et al.]
[arXiv:1802.07237: J. A. Aguilar Saavedra, et al.]
[arXiv:1910.03606: I. Brivio, et al.]
[arXiv:2212.05067: Aoude, Maltoni, Mattelaer, Severi, Vryonidou]

Flavour:
[arXiv:2101.07273: Bruggisser, Schäfer, van Dyk, Westhoff]
[arXiv:2003.05432: Aoude, Hurth, Renner, Shepherd]

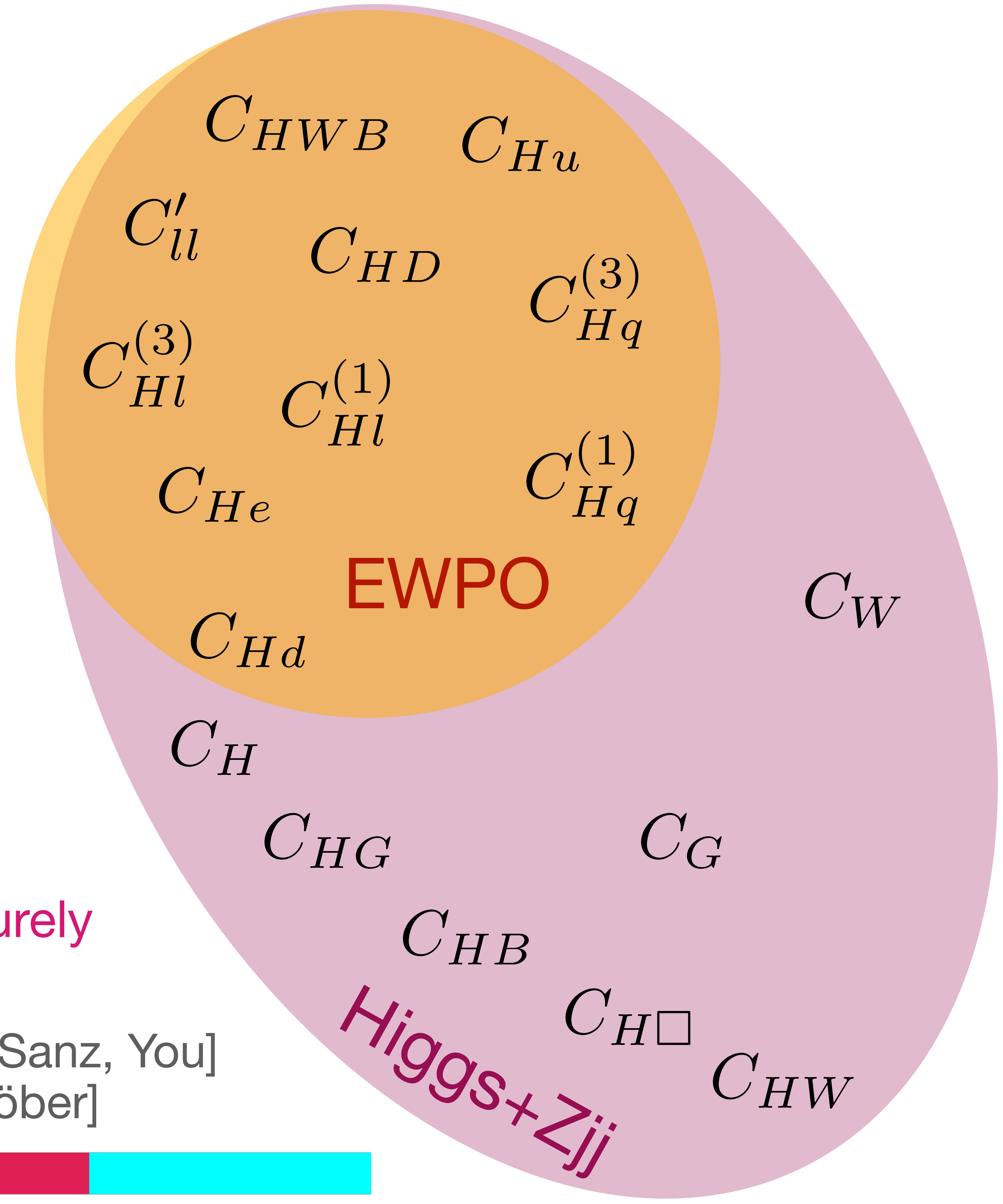
and many others…

In this work:

- The operator selection comes purely from symmetry assumptions;
- NLO observables have been included in a global fit without flat directions;
- Dijets observables are included in a consistent way.

Datasets

EWPO:
Dominantly constrain these 10 operators, but leaves two flat directions.
[1909.02000: Dawson, Giardino]



Higgs:
Breaks EW flat directions and constrains some additional purely boson operators.
[2012.02779: Ellis, Madigan, Mimasu, Sanz, You]
[2202.02333: Alasfar, de Blas, Gröber]

Constrained operators: 17

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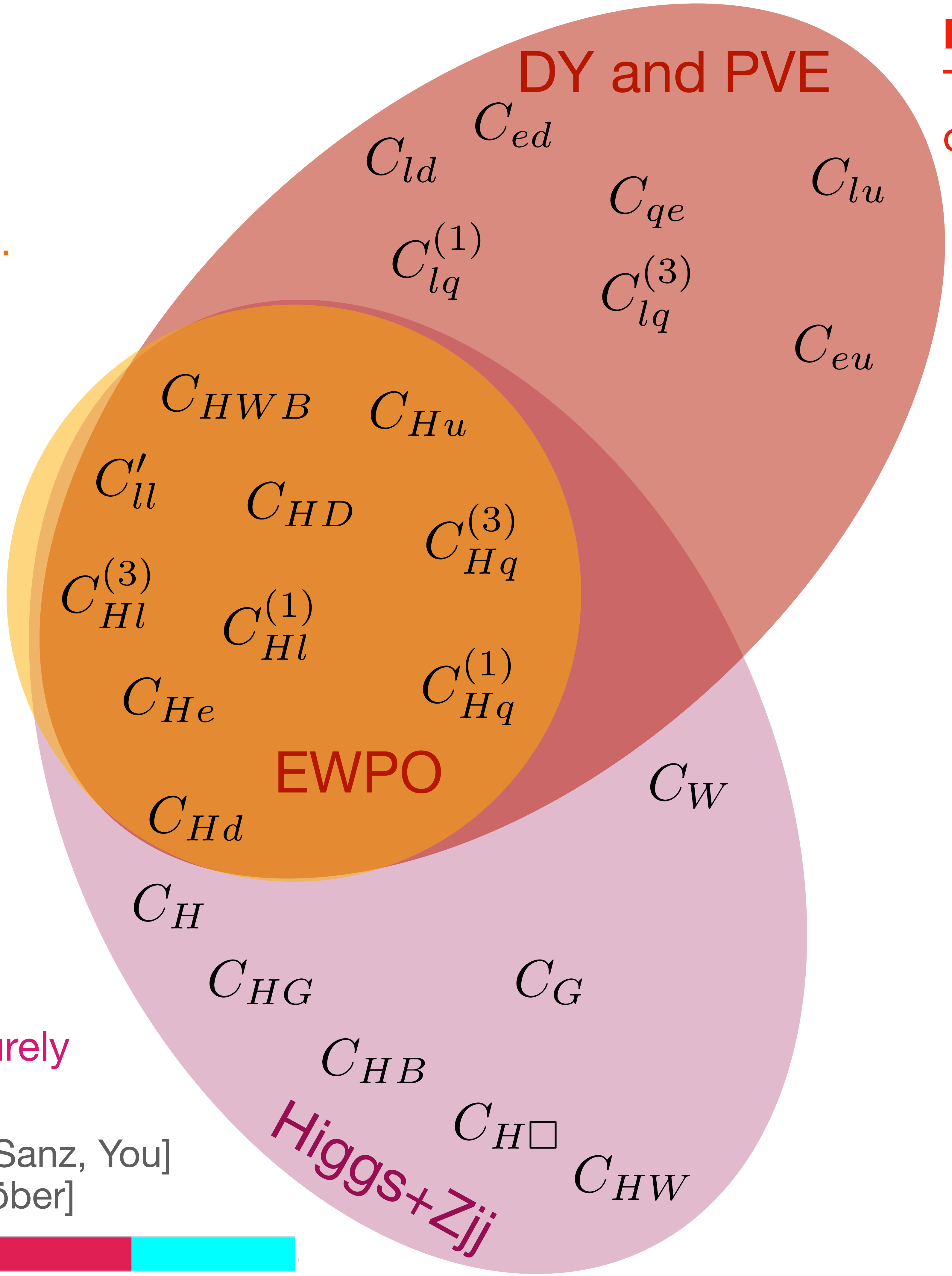

Drell-Yan and PVE:
Their interplay is needed in order to constrain semi-leptonic operators.
[2207.10714: Allwicher et al.]
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Constrained operators: 24

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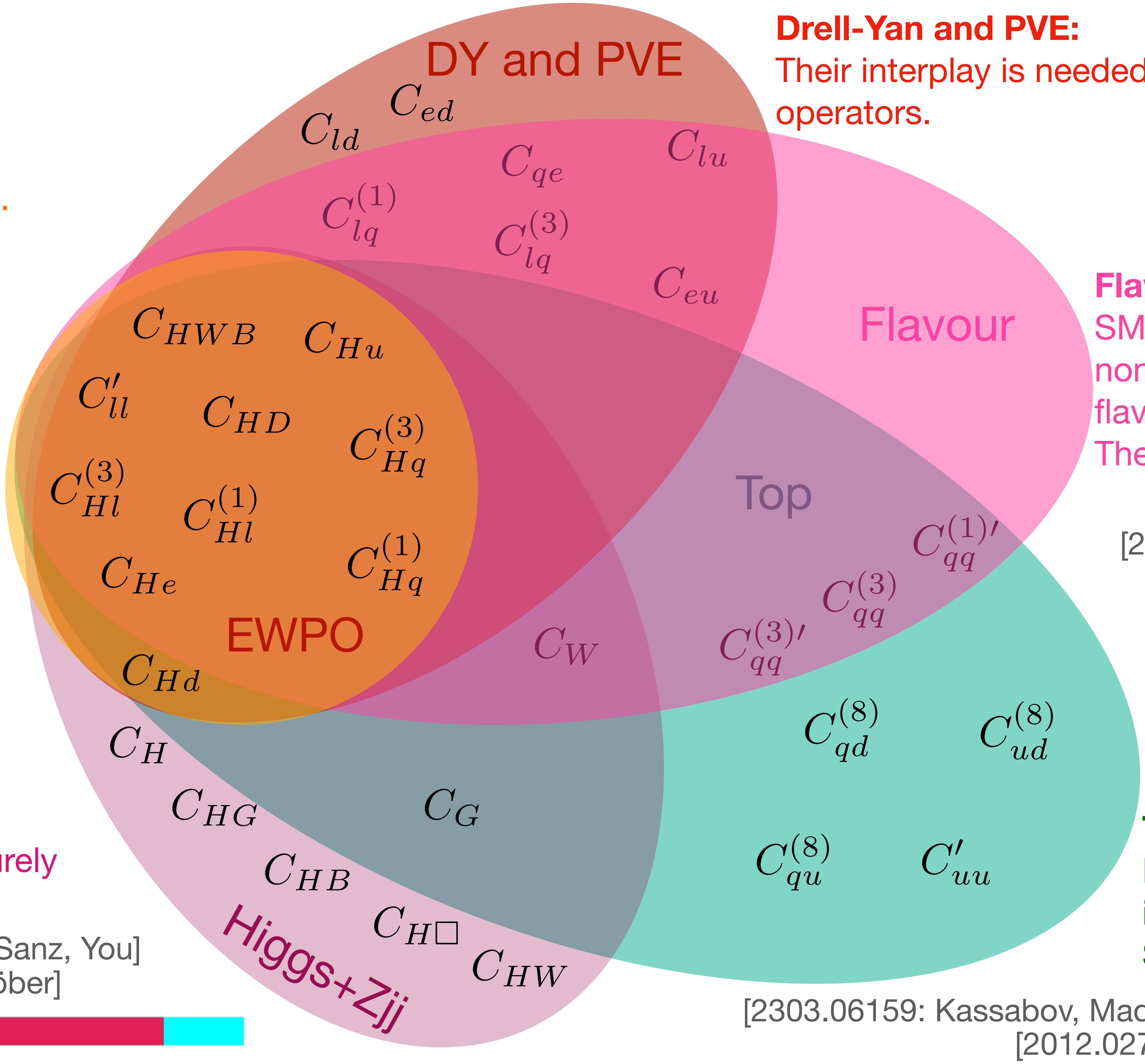

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Flavour:
SMEFT operators are flavour symmetric, nonetheless Yukawa couplings give rise to flavour violating observables via loop.
These bounds lift correlations present in Top.
[1810.08132: Straub]
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Top:
Put constraints on 4-quark operators involving up-type quark.
Some operators suffer from correlations.
[2303.06159: Kassabov, Madigan, Mantani, Moore, Alvarado, Rojo, Ubiali]
[2012.02779: Ellis, Madigan, Mimasu, Sanz, You]

Constrained operators: 31

Datasets

EWPO:
Dominantly constrain these 10 operators, but leaves two flat directions.
[1909.02000: Dawson, Giardino]

Lepton scattering:
Constrain mainly purely leptonic-operators
[1706.03783: Falkowski, Gonzalez-Alonso, Mimouni]

Higgs:
Breaks EW flat directions and constrains some additional purely boson operators.
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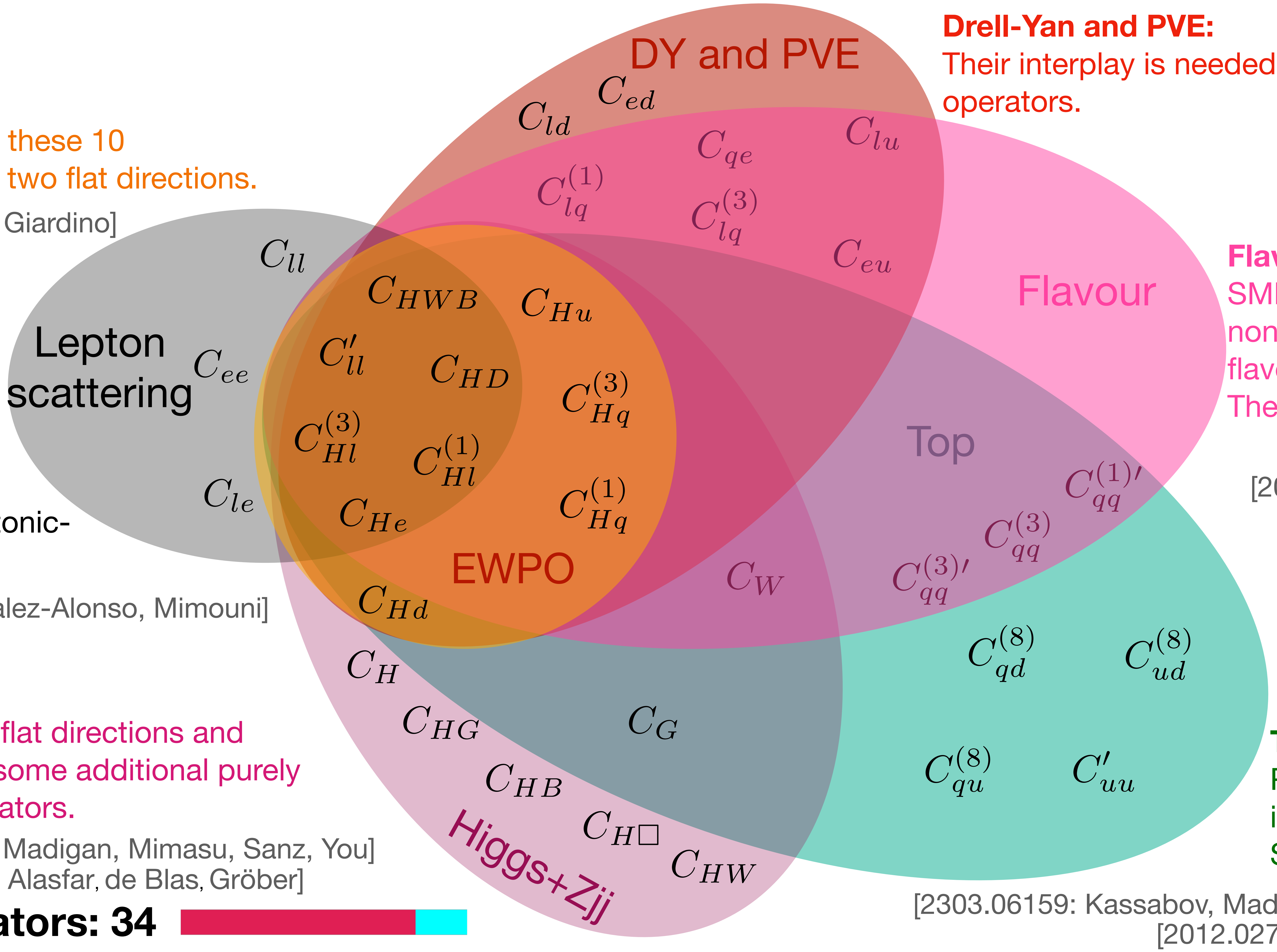
[2202.02333: Alasfar, de Blas, Gröber]



Constrained operators: 34

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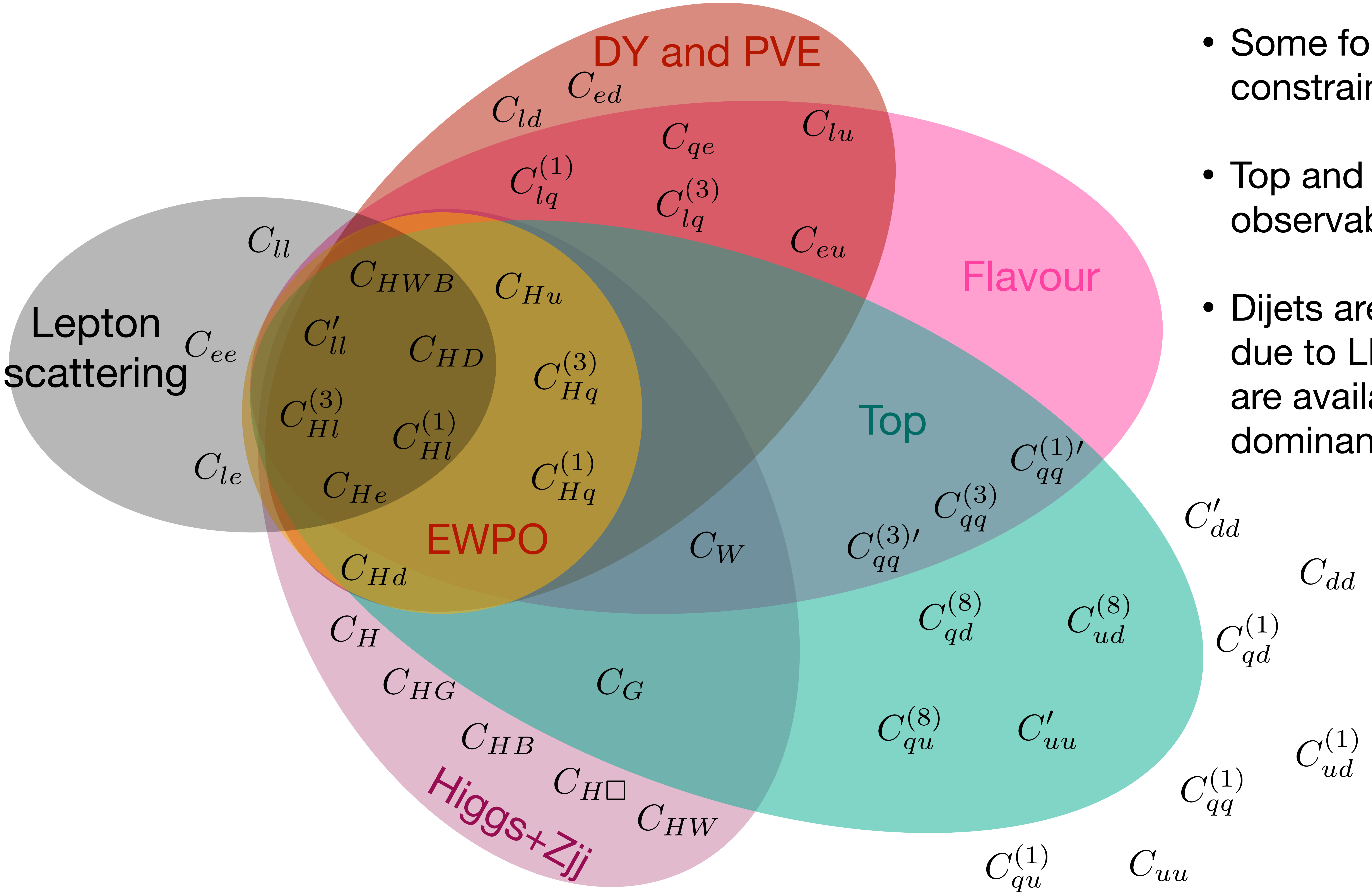
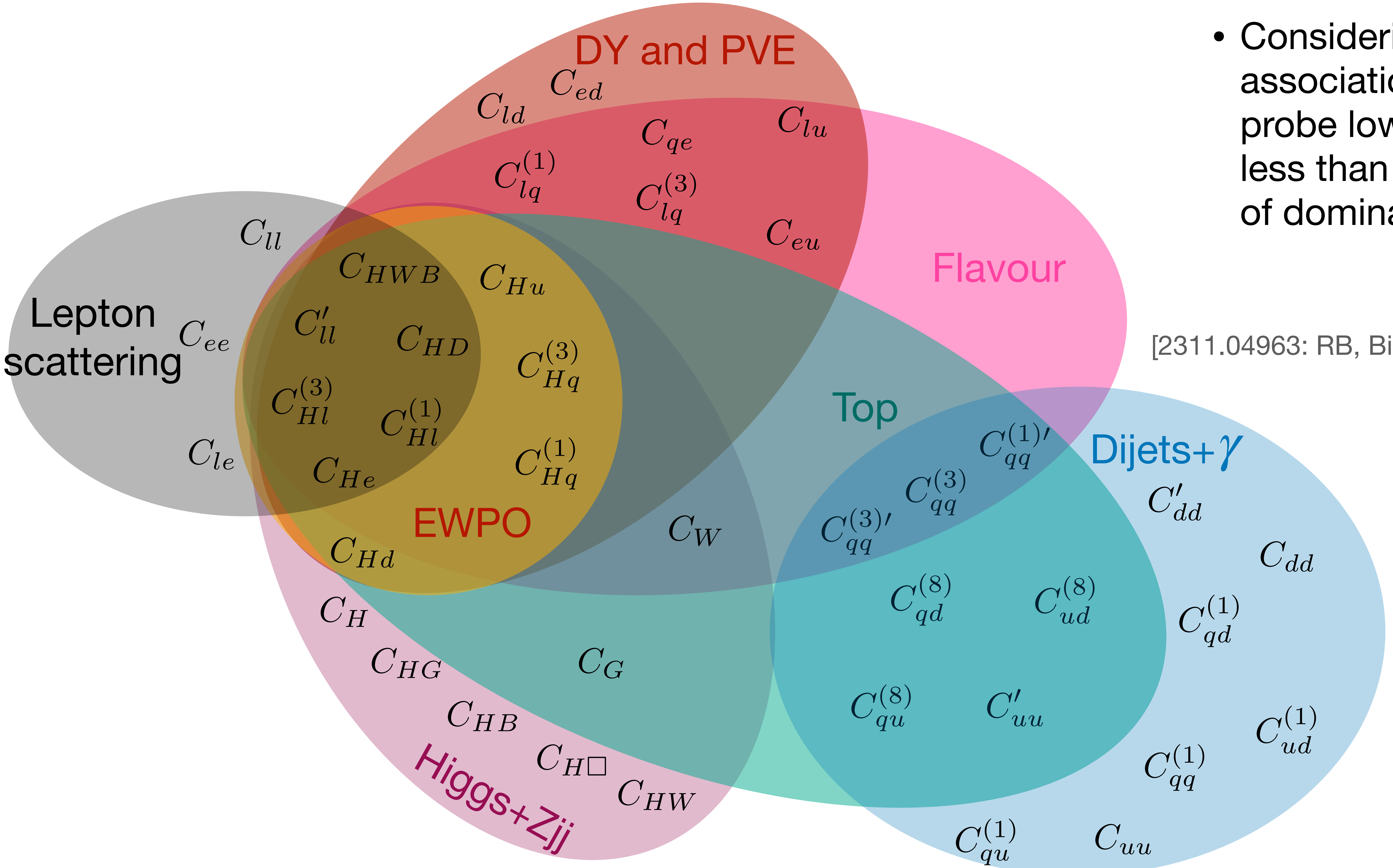
Dijets+γ



- Some four-quark operators are particularly hard to constrain.
- Top and flavour cannot constrain them and also NLO observables are not enough to get constraints.
- Dijets are the perfect observable to address them, but due to LHC trigger thresholds, only very high energy data are available, possibly leading to inconsistency: dominant quadratic terms, breaking of the EFT validity.

Constrained operators: 34

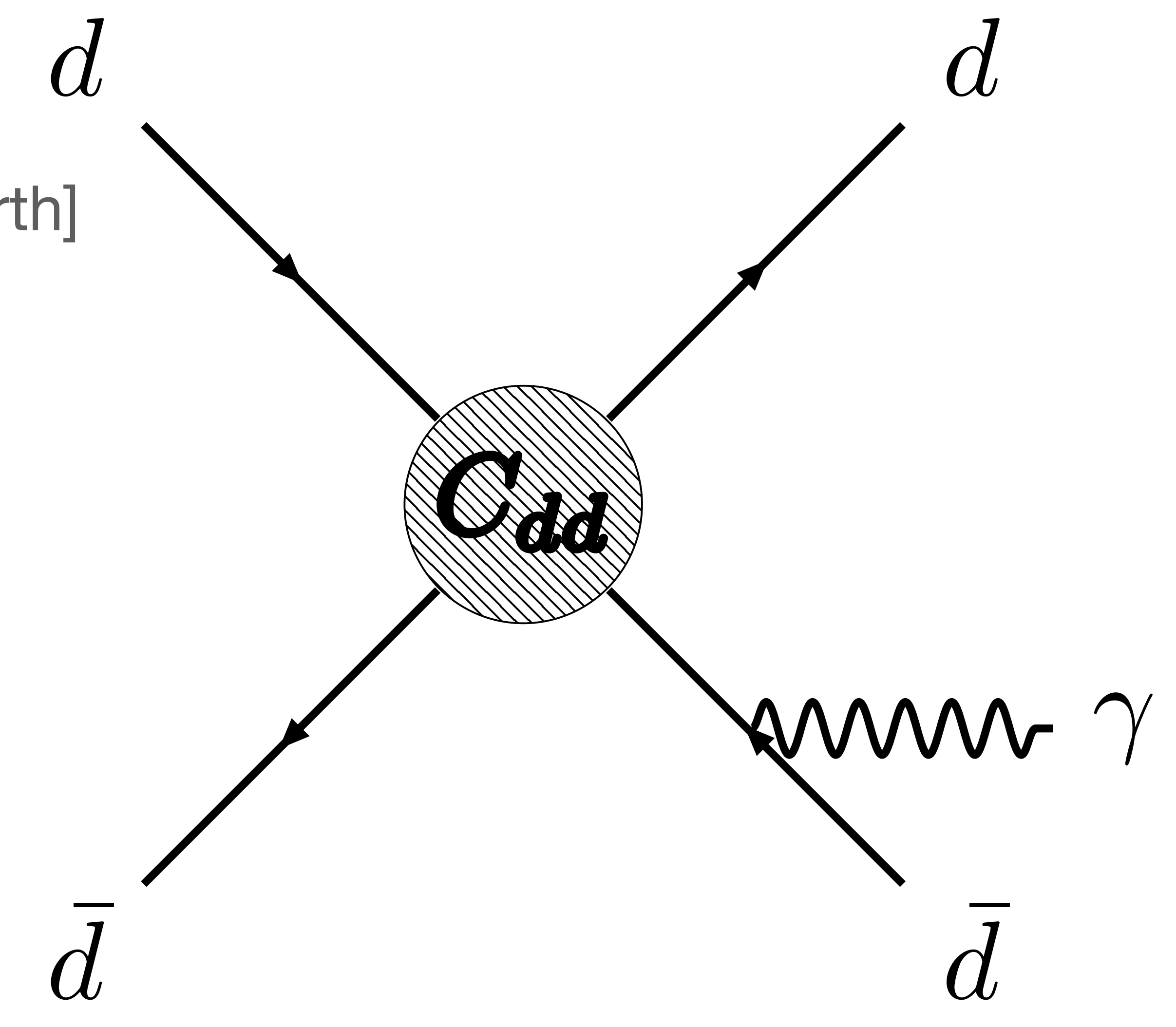
Dijets+γ



Constrained operators: 41

- Considering the production of two jets in association with a photon enables us to probe lower dijet invariant-mass ranges less than 1.1 TeV and circumvent the issue of dominant quadratic terms.

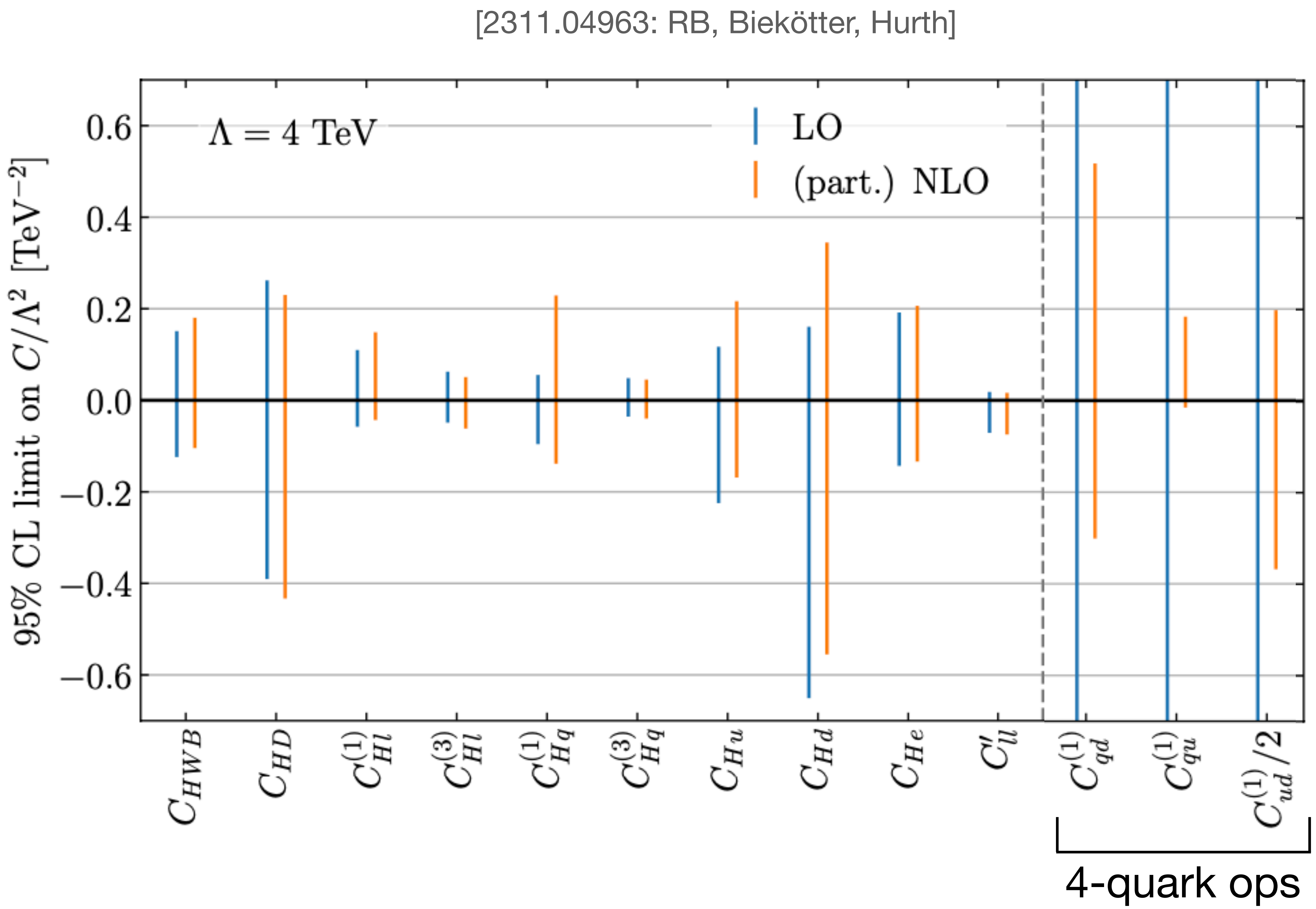
[2311.04963: RB, Biekötter, Hurth]



Dijet mass range: 225 GeV - 1.1 TeV

[ATLAS: 1901.10917]

LO vs NLO fit



- Some operators, poorly constrained using only LO observables, result much better bounded when NLO observables are included.

  Constraints on $C_{qu}^{(1)}$ at LO: Dijets

  Constraints on $C_{qu}^{(1)}$ at LO+NLO: Dijets, Higgs, EWPO, Top

LO vs NLO fit

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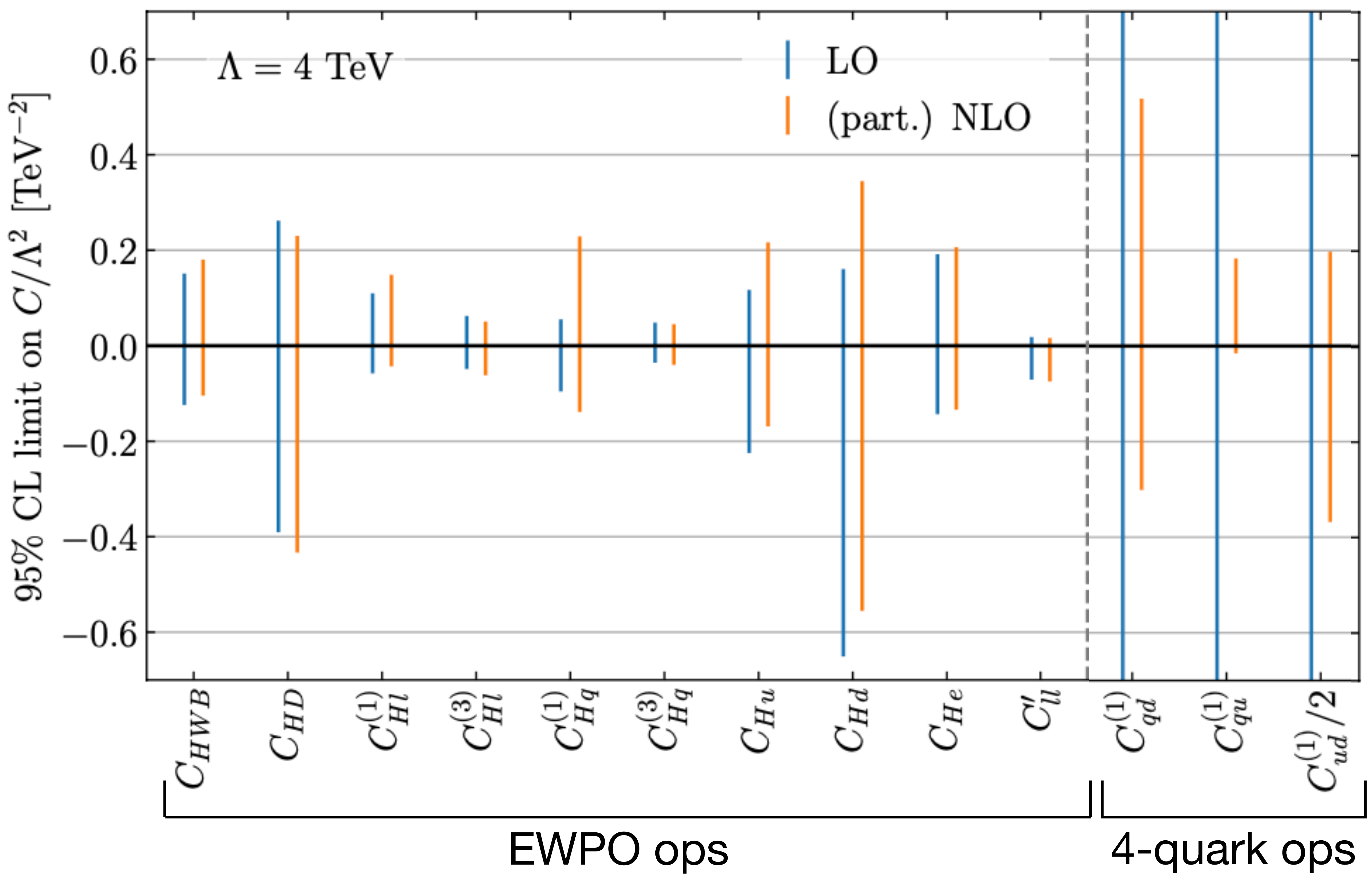

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  Constraints on $C_{qu}^{(1)}$ at LO: Dijets

  Constraints on $C_{qu}^{(1)}$ at LO+NLO: Dijets, Higgs, EWPO, Top

- Even after the inclusion of NLO predictions for EWPO observables, the bounds on EW operators did not significantly change.

  Number of operators occurring in EWPO at LO: 10

  Number of operators occurring in EWPO at NLO: 35

Summary

- In order to fit all the 41 coefficients of the minimal MFV SMEFT, without flat directions, an extremely various dataset is needed, consisting of about 600 observables.

- Dijet-photon production consistently bounds a set of 4-quark operators otherwise hard to constrain.

- NLO observables can be successfully implemented in global analyses improving the bounds for some poorly constrained operators.

Summary

- In order to fit all the 41 coefficients of the minimal MFV SMEFT, without flat directions, an extremely various dataset is needed, consisting of about 600 observables.
- Dijet-photon production consistently bounds a set of 4-quark operators otherwise hard to constrain.
- NLO observables can be successfully implemented in global analyses improving the bounds for some poorly constrained operators.

Thank you for your attention!

Back up

Warsaw basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu} e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu} u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu} u_t)$		

Flavour symmetris in the SMEFT

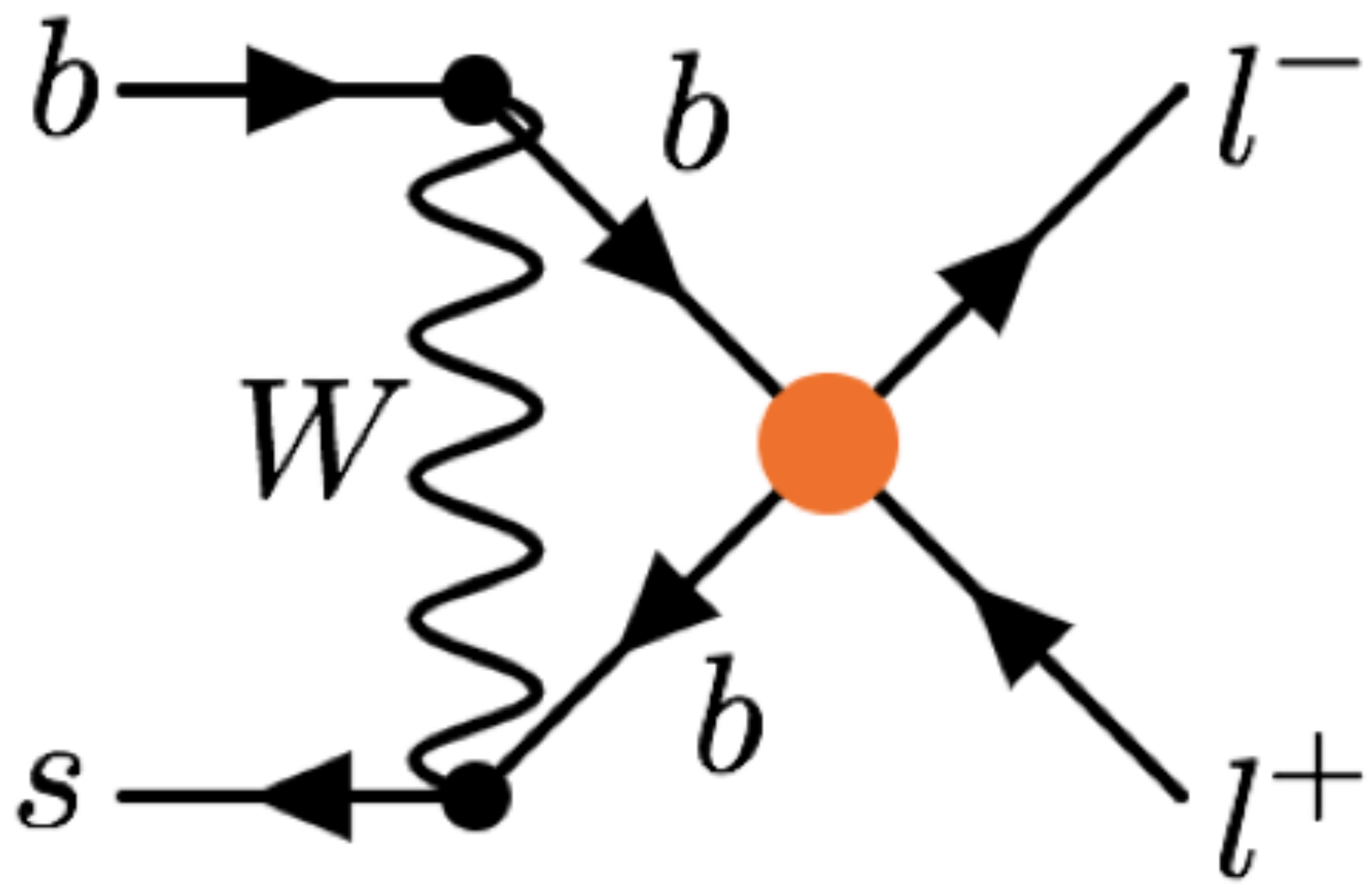
Class	Operators	No symmetry 3 Gen.		No symmetry 1 Gen.		$U(3)^5$ Exact		$\mathcal{O}(Y^1_{e,d,u})$		$\mathcal{O}(Y^1_e, Y^1_d Y^2_u)$	
1–4	X^3, H^6, H^4D^2, X^2H^2	9	6	9	6	9	6	9	6	9	6
5	ψ^2H^3	27	27	3	3	–	–	3	3	4	4
6	ψ^2XH	72	72	8	8	–	–	8	8	11	11
7	ψ^2H^2D	51	30	8	1	7	–	7	–	11	1
8	$(\bar{L}L)(\bar{L}L)$	171	126	5	–	8	–	8	–	14	–
	$(\bar{R}R)(\bar{R}R)$	255	195	7	–	9	–	9	–	14	–
	$(\bar{L}L)(\bar{R}R)$	360	288	8	–	8	–	8	–	18	–
	$(\bar{L}R)(\bar{R}L)$	81	81	1	1	–	–	–	–	–	–
	$(\bar{L}R)(\bar{L}R)$	324	324	4	4	–	–	–	–	4	4
total:		1350	1149	53	23	41	6	52	17	85	26

Table 1: Number of independent operators in $U(3)^5$, MFV and without symmetry. In each column the left (right) number corresponds to the number of CP-even (CP-odd) coefficients. $\mathcal{O}(X^n)$ stands for including terms up to $\mathcal{O}(X^n)$.

[2005.05366: Faroughy, Isidori, Wilsch, Yamamoto]

Flavour violation in MFV SMEFT

Since the full theory contain the same amount of flavour violation as the SM does, flavour violating observables are generated via loops.



[2003.05432: Aoude, Hurth, Renner, Shepherd]

Flavour violation in MFV SMEFT

Observables in the SMEFT are given by:

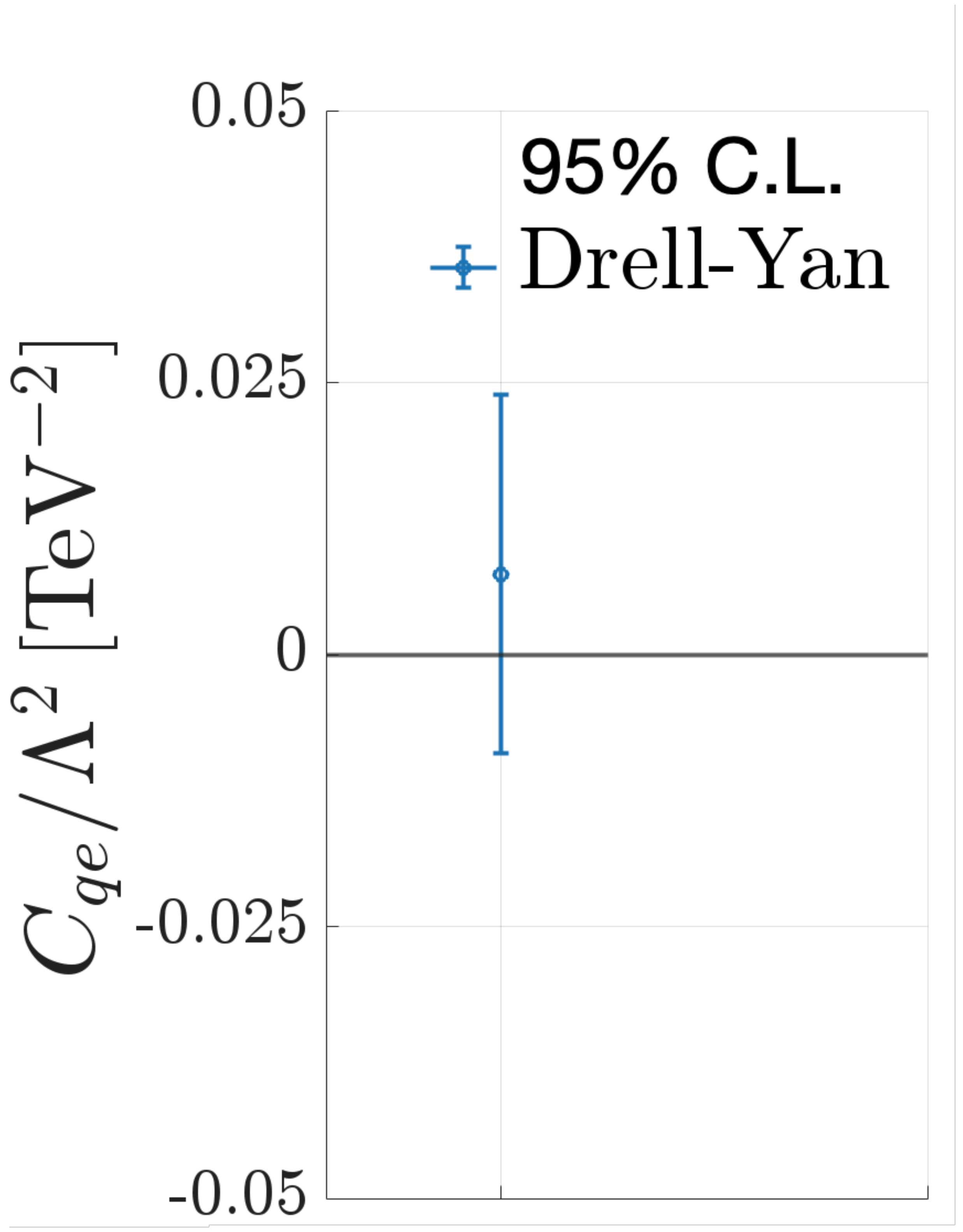
$$\sigma \propto |\mathcal{A}|^2 = \underbrace{|\mathcal{A}_{\text{SM}}|^2}_{\text{SM background}} + \underbrace{\frac{2C_6}{\Lambda^2}\text{Re}(\mathcal{A}_{\text{d6}}\mathcal{A}^*_{\text{SM}})}_{\text{signal}} + \underbrace{\frac{C_6^2}{\Lambda^4}|\mathcal{A}_{\text{d6}}|^2 + \frac{2C_8}{\Lambda^4}\text{Re}(\mathcal{A}_{\text{d8}}\mathcal{A}^*_{\text{SM}})}_{\text{theoretical uncertainty}} + \dots$$

When quadratic terms become relevant we cannot neglect anymore theoretical uncertainty.
Cross sections for 4-quark operators increase with the energy.

$$\sigma \propto \frac{|C_{dd}|^2}{\Lambda^4} s$$

Correlations and flat directions

Bounds on Wilson coefficients are obtained comparing theoretical predictions and experimental limits:



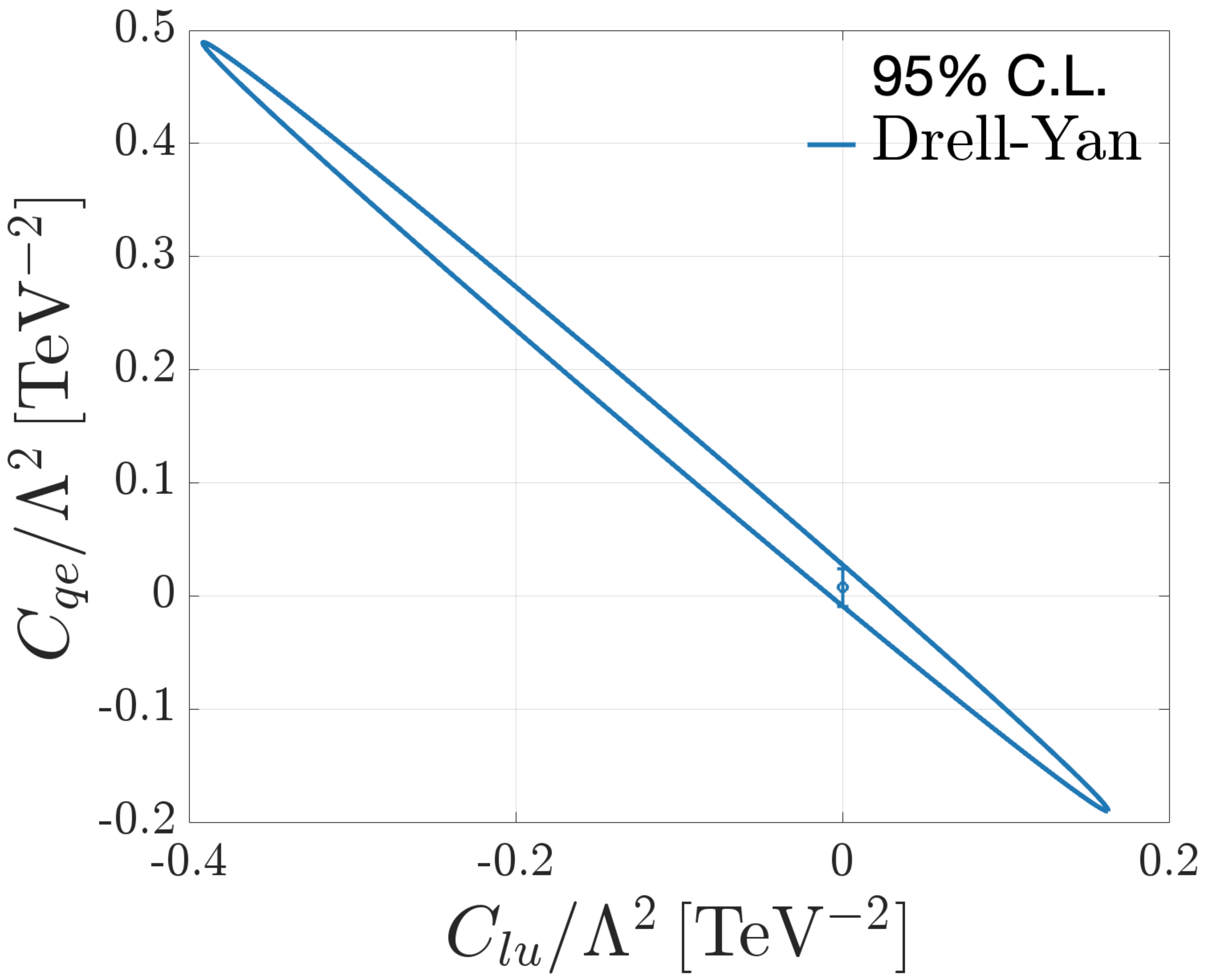
- Drell-Yan process significantly constrains semi-leptonic operators.

  [2207.10714: Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch]

[2311.04963: RB, Biekötter, Hurth]

Correlations and flat directions

Bounds on Wilson coefficients are obtained comparing theoretical predictions and experimental limits:



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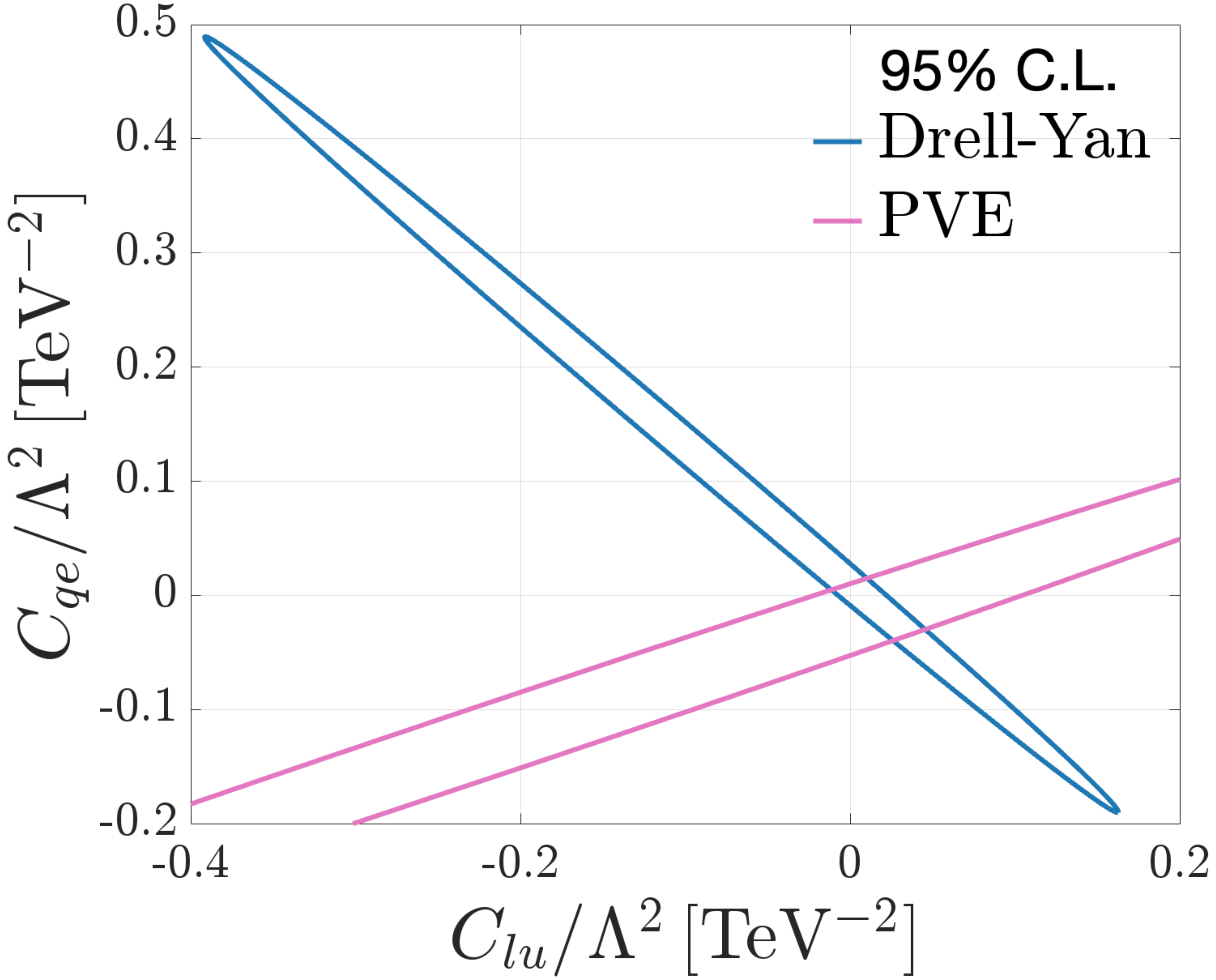

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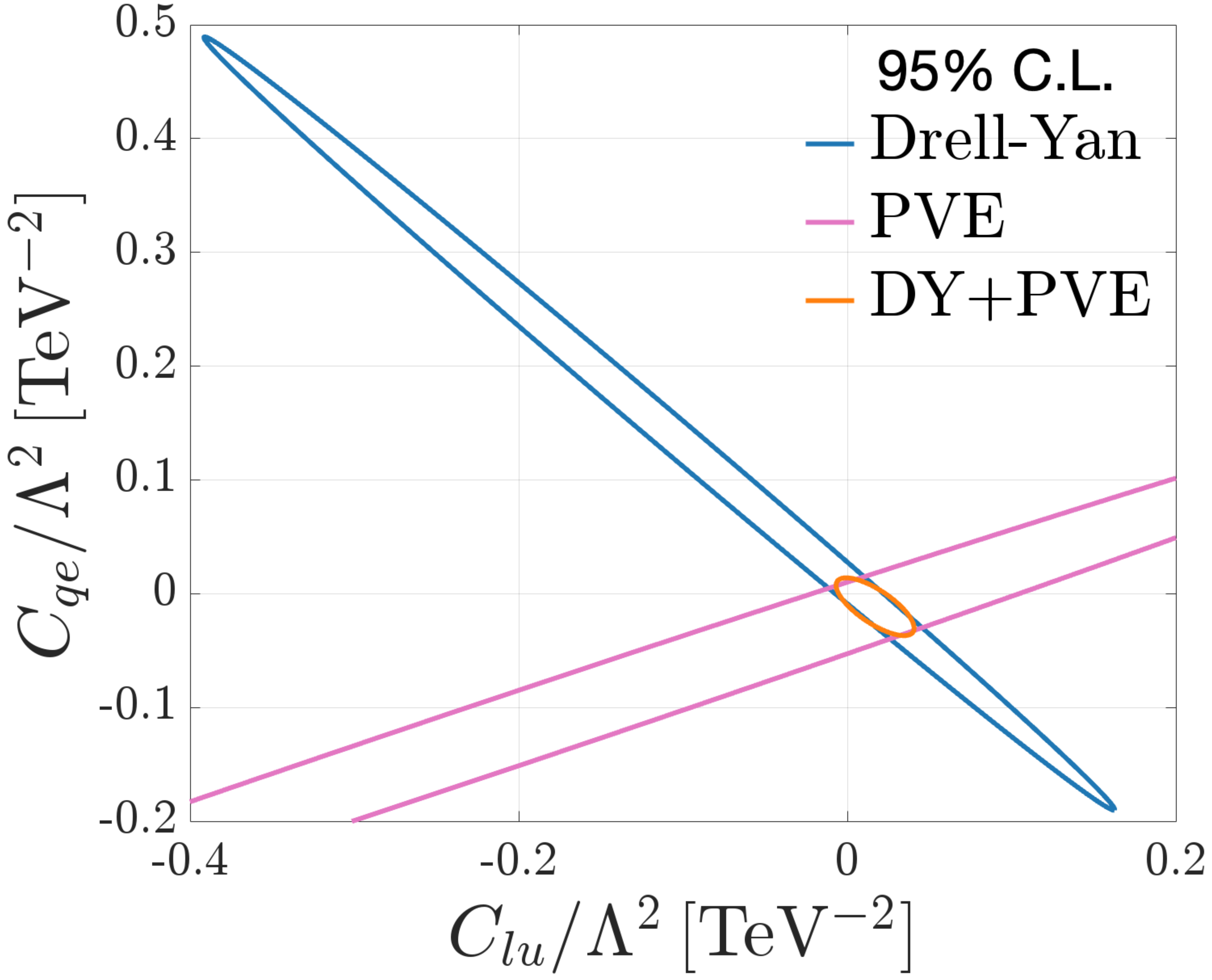

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Models compatible with our assumption

These scalar extensions of the SM match at 1-loop only on flavour symmetric operators:

Complex colour sextet, isospin singlet: $\chi_3 \equiv (6_C, 1_L, -\frac{2}{3}|_Y)$

$$\mathcal{L}_{\chi_3} = \mathcal{L}_{\rm SM}^{d\leq 4} + (D_\mu \chi_3)^\dagger (D^\mu \chi_3) - m_{\chi_3}^2 \chi_3^\dagger \chi_3 - \eta_{\chi_3} H^\dagger H \chi_3^\dagger \chi_3 - \lambda_{\chi_3} \left(\chi_3^\dagger \chi_3\right)^2$$
$$- \left\{ y_{\chi_3} \left(d_R^{\{A|}\right)^T C \left(\chi_3^{AB}\right)^\dagger d_R^{|B\}} + \text{h.c.} \right\}$$

Complex Singlet: $\mathcal{S}_2 \equiv (1_C, 1_L, 2|_Y)$

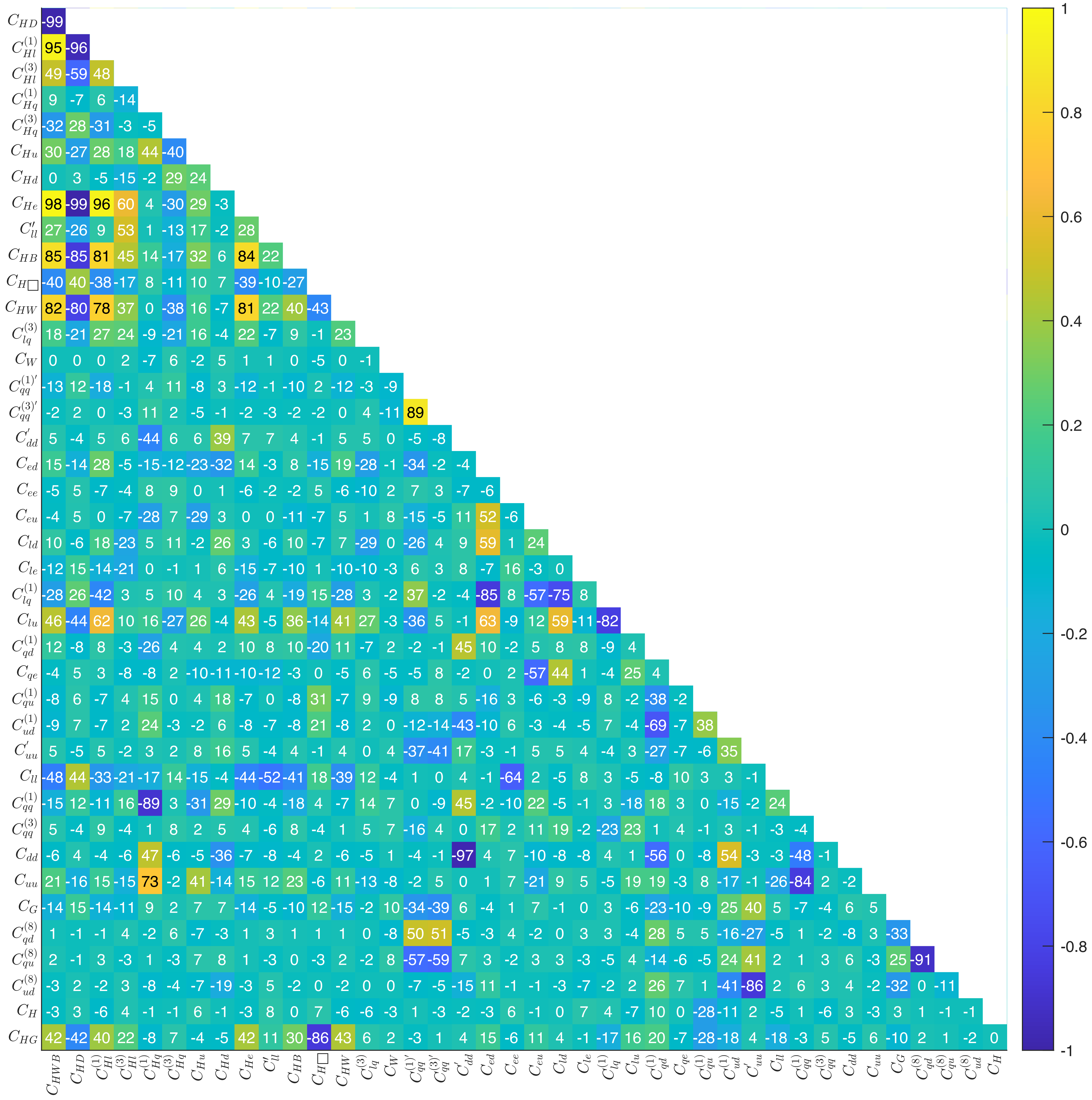
$$\mathcal{L}_{\mathcal{S}_2} = \mathcal{L}_{\rm SM}^{d\leq 4} + (D_\mu \mathcal{S}_2)^\dagger (D^\mu \mathcal{S}_2) - m_{\mathcal{S}_2}^2 \mathcal{S}_2^\dagger \mathcal{S}_2 - \eta_{\mathcal{S}_2} |H|^2 |\mathcal{S}_2|^2 - \lambda_{\mathcal{S}_2} |\mathcal{S}_2|^4$$
$$- \left\{ y_{\mathcal{S}_2} e_R^T C\, e_R\, \mathcal{S}_2 + \text{h.c.} \right\}$$

Complex colour triplet, isospin singlet: $\varphi_2 \equiv (3_C, 1_L, -\frac{4}{3}|_Y)$

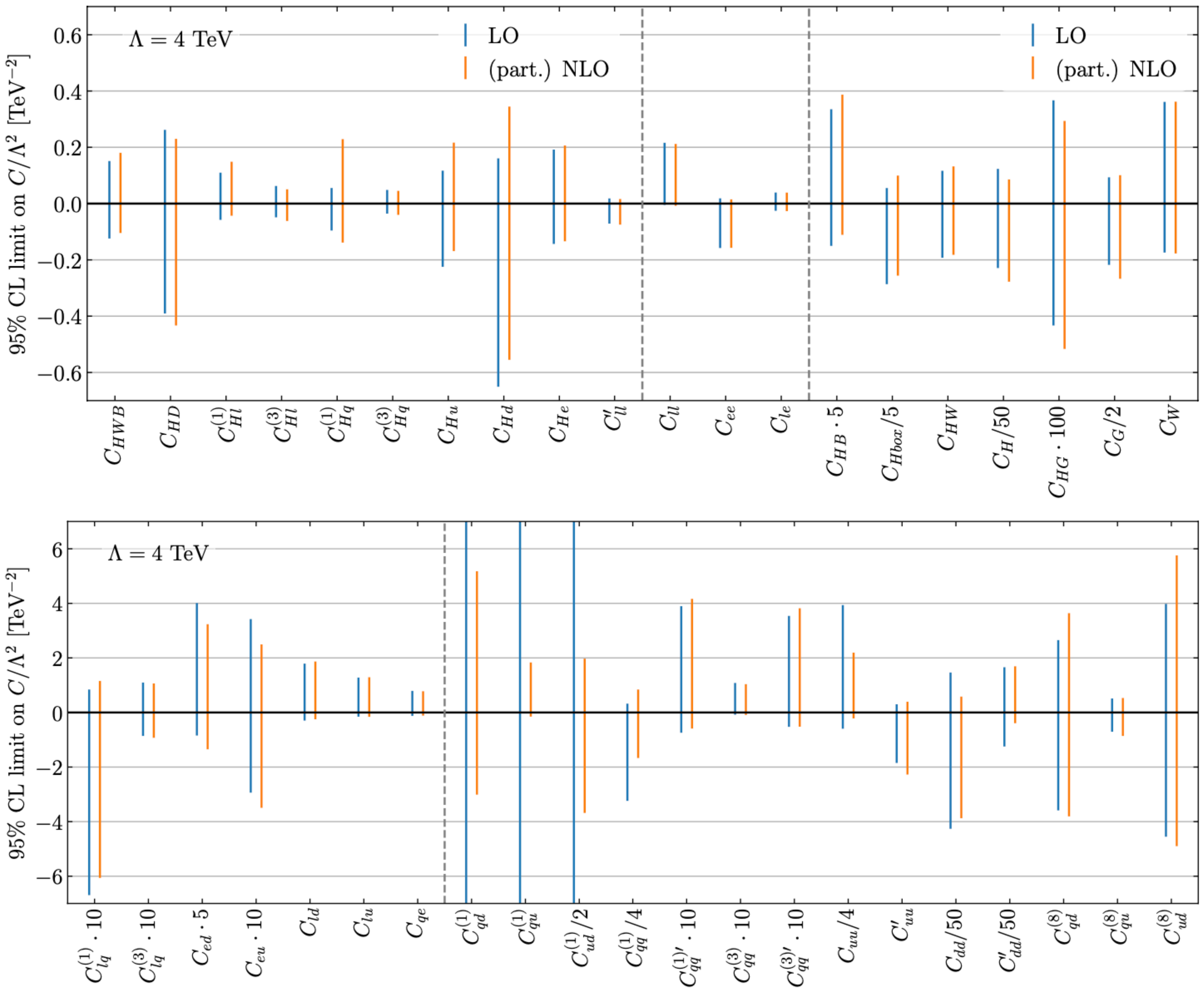
$$\mathcal{L}_{\varphi_2} = \mathcal{L}_{\rm SM}^{d\leq 4} + (D_\mu \varphi_2)^\dagger (D^\mu \varphi_2) - m_{\varphi_2}^2 \varphi_2^\dagger \varphi_2 - \eta_{\varphi_2} H^\dagger H \varphi_2^\dagger \varphi_2 - \lambda_{\varphi_2} \left(\varphi_2^\dagger \varphi_2\right)^2$$
$$+ \left\{ y_{\varphi_2} \varphi_2^{\alpha\dagger} d_R^{\alpha\, T} C e_R + \text{h.c.} \right\}$$

[arXiv:2111.05876: Anisha, Das Bakshi, Banerjee, Biekötter, Chakrabortty, Patra, Spannowsky]

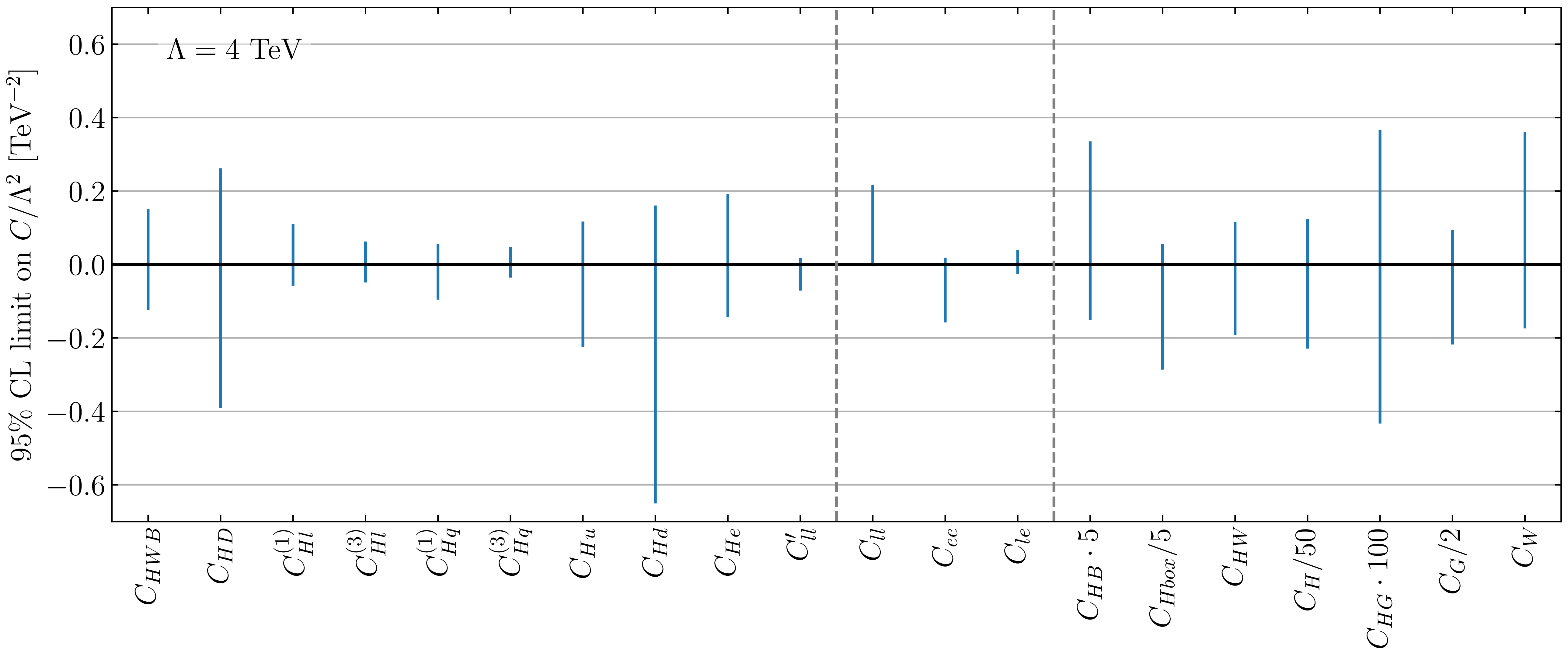
Correlation matrix

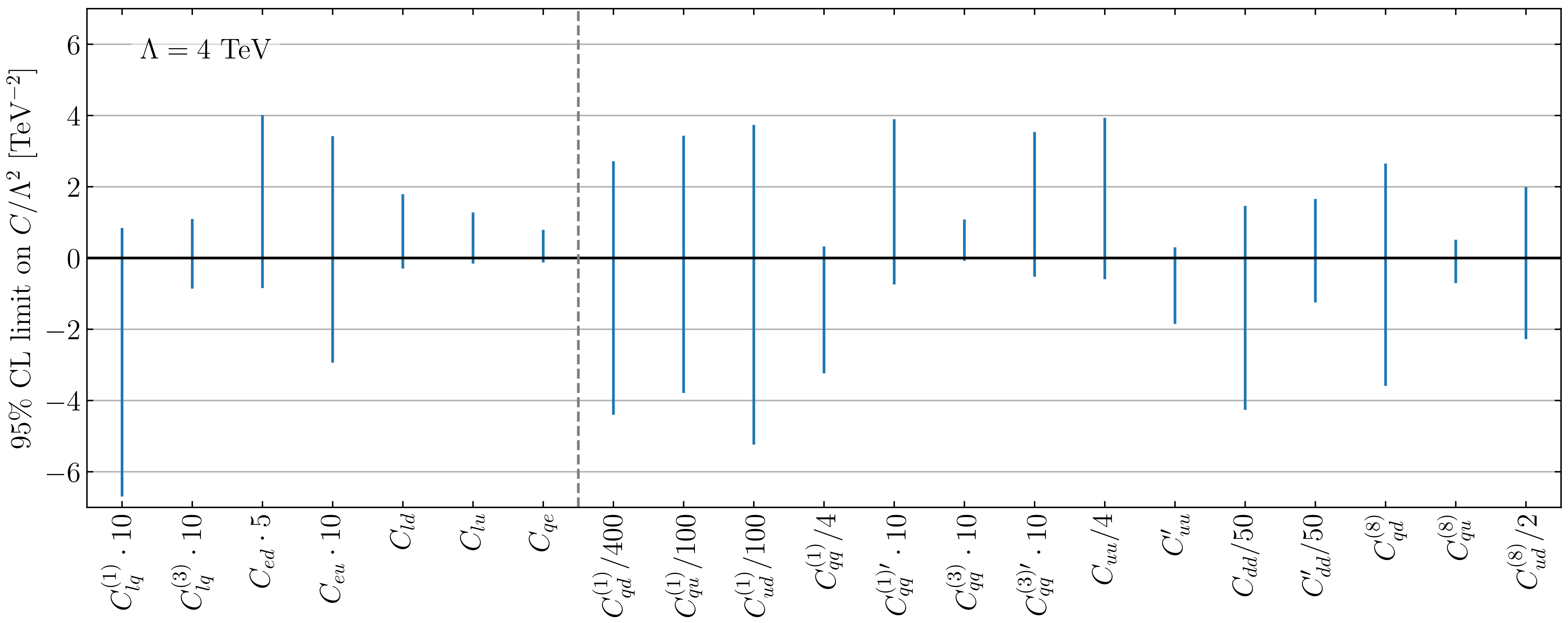


Full LO vs NLO results



Full NLO results





Full results removing datasets